Valuation of Ecosystem Services from Improved Soil Health in Vermont

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Executive Summary:

For millennia, farmers have recognized the importance of soil health for crop productivity and resilience. Recently, scientists, policy-makers and farmers have become interested in the non-agricultural benefits of healthy farmland soils. Healthy soils can support climate mitigation through carbon sequestration, protect the health of waterways by retaining nutrients and sediments, protect downstream communities by absorbing water and protect the air by regulating gaseous emissions. These and other ecosystem services provided by healthy soils may meaningfully contribute to the health and vitality of communities and ecosystems.

In recent years, farms have struggled financially and awareness of environmental problems have grown. Across the world, policy-makers have sought ways to compensate family farms for their environmental stewardship as a means to tackle both these problems. Farmers have organized under the banner of “regenerative agriculture” to experiment with new practices and promote the values that healthy soil can provide far beyond the farm.

Vermont may be well-positioned to become a leader in this movement; family farming and environmental stewardship are central to our collective identity and economy. There have been several efforts to develop a policy framework for soil stewardship, but none have succeeded. In 2019, Act 83 of the Vermont Legislature created a working group to explore payments for ecosystem services as a framework for linking farm supports and environmental stewardship. This report was commissioned as part of this effort.

To design a program to promote soil ecosystem services, it is necessary to generate an estimate of the magnitude of each of the benefits. Without understanding the scale and value of benefits, we cannot judge the cost-effectiveness of such a program compared with alternatives, such as investments in other natural systems, such as forests and wetlands, or investments in hard infrastructure. Because improvements in natural systems can affect many different things we care about, putting total benefits in dollar terms helps us to combine different types of benefits, and also to assess which benefits need closer examination.

In this report, we present estimates for ecosystem services generated by soil-health practices, and improvements in soil-health indicators, for four different services. For soil-health practices, such as converting annual crops to hay, we utilize a set of off-the shelf empirical models widely used to estimate ecological functions on farm landscapes. For

soil-health indicators, we make estimates link these tools with soil data and statistical models describing how soil-health parameters influence the interaction of soils with water and their environment. We provide rough monetary estimates of the value of these services, using several different standard ecological economics methods. These results are necessarily rough, but can help to elucidate the relative magnitudes of different types of benefits.

Overall, improvements in soil health, and uptake of soil health practices have the potential to produce substantial benefits for Vermonters, and people around the world.

Flood mitigation benefits have the lowest valuations, but also the most spatially variable. Average values are roughly $.66/acre/year the “best” scenario and $.30/acre/year for the “good” scenario. These small values are largely because most farmland in Vermont has very few downstream neighbors at risk- a small minority of farm fields have potential flood-mitigation values 5x or 10x higher.

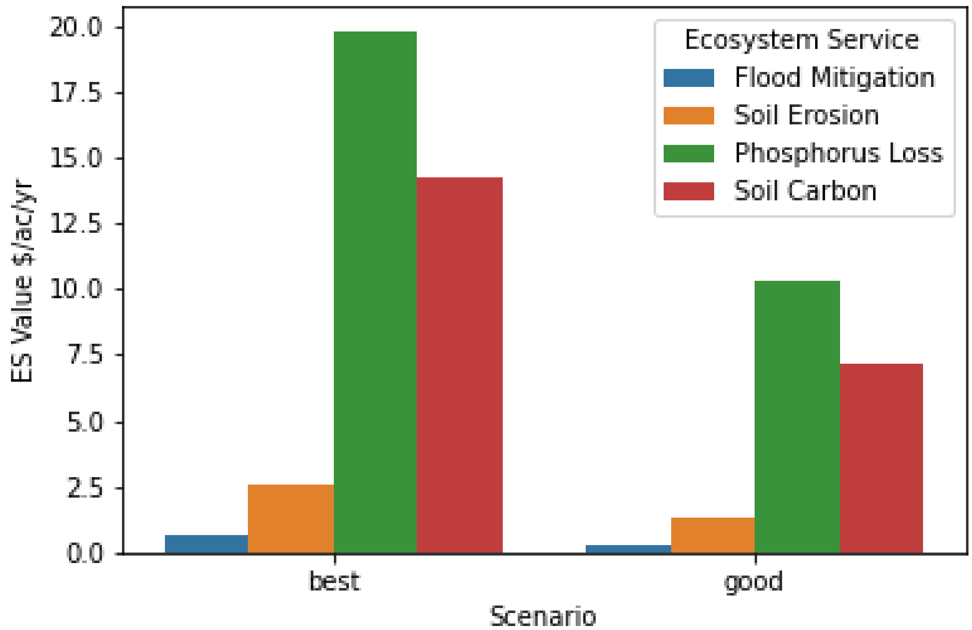
Erosion reduction benefits are also relatively small for most farm fields- $1.30/acre for the “good” scenario and $2.59 for the best scenario. These benefits are proportional to the scale of current erosion losses; fields that are flat and already have extensive soil-cover will see much smaller reductions than steeper fields or those currently in row-crops.

Phosphorus retention Benefits are the largest in dollar terms, but also the one with the largest scientific uncertainty. Average values for the good scenario are $10.36, while average values for the best scenario are $19.78. Improved soil health is likely to ***not*** reduce P loading from soils with pattern tile drainage or other direct sub-surface connections to surface-water. Like erosion, P-mitigation benefits from improvements in soil health are highest where potential for P loss is highest, and in watersheds where P loading is a larger problem.

Carbon Storage Benefits are substantial, valued at $14.26/ac/year in the “best” scenario, and $7.13/ac/year in the “good” scenario. We calculate these based on the reduction in warming each year due to reduced atmospheric carbon, which avoids the problem of “impermanence” and would allow indefinite annual payments to farmers.

Nitrogen Retention Benefits are harder to characterize as nitrogen can leave farm fields and damage the environment in a myriad of ways; and practices and soil conditions that reduce one pathway may increase another. We present general estimates of the magnitude of harms from N losses from Vermont farms and demonstrate that these harms are large enough that moderate mitigation would generate substantial benefits.

Soil Biodiversity Benefits could be valued in a number of ways, but producing a monetary valuation was beyond the scope of this report.



Under the “best” scenario of improvement, we estimate that farms could be credited with an average of >$37/acre/year in ecosystem services . Under the “good” improvement scenario, farms   could be credited i for $19.

Introduction:

Scope:

This report estimates the impacts of soil health practices and soil health improvements on several regulating ecosystem services for the state of Vermont, and provides rough estimates of the monetary values of these improvements. The ecosystem services estimated in this paper are: climate mitigation, nutrient retention, erosion control, flood mitigation. We also briefly address impacts of soil health on nitrogen cycling and pollution, but complexity and uncertainty prevents us from estimating values. While soil health has numerous benefits to yield, crop quality and climatic resilience for the individual farmers and landowners, these benefits are outside of the scope of this report. Instead, we focus on public goods provided to society at large, to inform a potential PES scheme for soil health in Vermont.

Methods:

This report estimates ecosystem services and their values using two distinct perspectives. First, we estimate the increase in ecosystem services from ***soil health practices***, using the scenarios developed for Task 2 as examples. For this, we use an array of existing empirical models, including the Universal Soil Loss Equation, the Curve Number Method and the Vermont Phosphorus Index to estimate the change in ecosystem services.

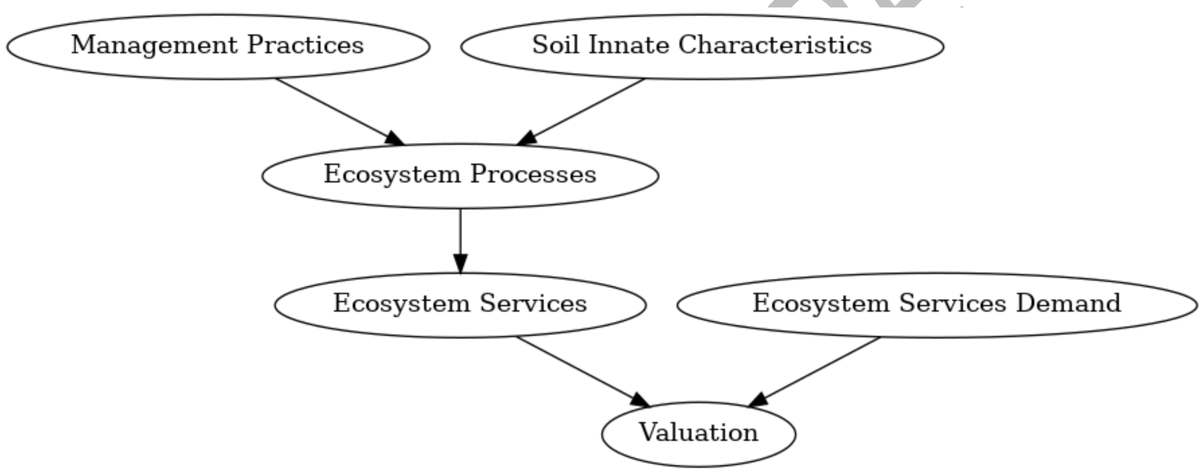


Figure: Conceptual Model for Estimating Impacts of Soil Health Practices on Ecosystem Services.

We also estimate impacts of changes in **soil-health *indicators*** on ecosystem services. We use data from the NRCS Soil Characterization Database to define innate characteristics and reference conditions for Vermont Soil Types. Innate characteristics are those that don't change with management, such as soil particle-size distribution. Reference conditions are used as typical baselines for conditions that are potentially impacted by management, such as Soil Organic Matter, Bulk Density and depth of each soil horizon. Soil innate characteristics and soil health indicators are used to simulate other soil properties, such as soil erodibility, plant available water capacity and saturated hydraulic conductivity. These parameters are then used to simulate changes to the ecosystem services of interest, using similar tools to those used for soil indicators.

We present two scenarios for moderate and large changes in soil-health, and estimate their impacts on various ecosystem services, as compared to the reference state of the soil.

These scenarios are:

"Best": Soil Organic Matter in the A horizon is 50% higher than the reference condition and bulk density 20% lower.

"Good" : Soil Organic Matter in the A horizon is 25% higher than the reference condition and bulk density 20% lower.

For each scenario, we simulate these changes on 10 different common agricultural soil-series: Tunbridge, Winooski, Agawam, Windsor, Covington, Vergennes, Cabot, Hadley, Hamlin and Georgia, and present average results, sometimes grouped by soil characteristics.

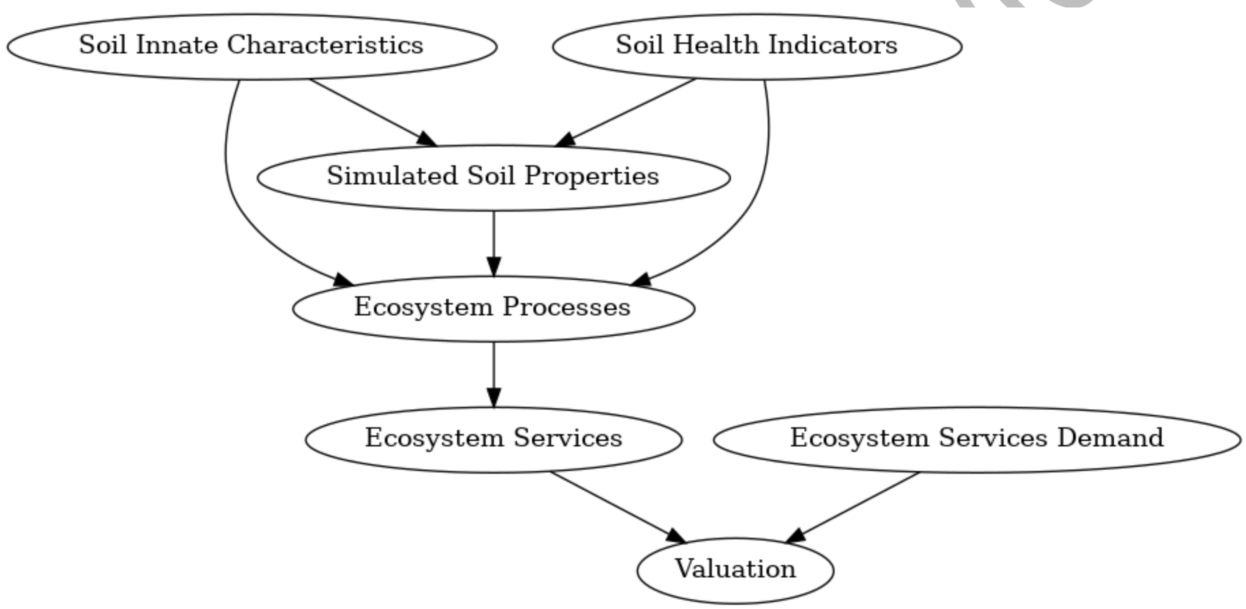


Figure: Conceptual Model for Ecosystem Services Assessment of Soil Health Indicators

We do not attempt to estimate the impact of soil health practices on soil health, and then the impacts of soil health on ecosystem services. We hesitate to do this because most tools used to assess the impact of practices on soil ecosystem functions and services do not allow us to partition between their *direct* impact on soil ecosystem services and their impact which is mediated through soil health. For instance, the NRCS Curve Number method estimates lower runoff from land that is in permanent grassland than land that is growing corn. This is due to improved soil health, greater vegetative cover and other differences, but the method gives us no way to disentangle the portion of the impact that is due to soil health itself.

Simulating Impacts of Soil Properties:

Bulk Density and Soil Organic Matter are important indicators of soil health, but their impacts on many important ecosystem processes, and therefore ecosystem services are mediated through their impacts on *other soil characteristics*. Many of these other soil characteristics can, in principle, be measured, but would not be feasible to include in a PES program. Instead, these characteristics, including Plant Available Water Capacity, Porosity, Saturated Hydraulic Conductivity and Soil Erodibility are simulated through a series of Pedo-transfer functions. These equations are used to estimate unknown soil properties based on known soil properties. Figure (x) below shows some of these relationships.

In this report we estimate the impacts of two different improvement scenarios for several different common Vermont Agricultural Soils and present averages of these results. The two improvement scenarios are the "best" scenario: Soil Organic Matter increases by 50% and bulk density declines by 20% and the "good" scenario: SOM increases by 25% and bulk density declines by 10%. In both scenarios, these improvements are confined to the upper layer (A horizon) of the soil, and the decrease in bulk density is compensated for by increasing the depth of the A horizon to keep the mass of soil in the A horizon constant.

Ecosystem Services:

Flood Mitigation:

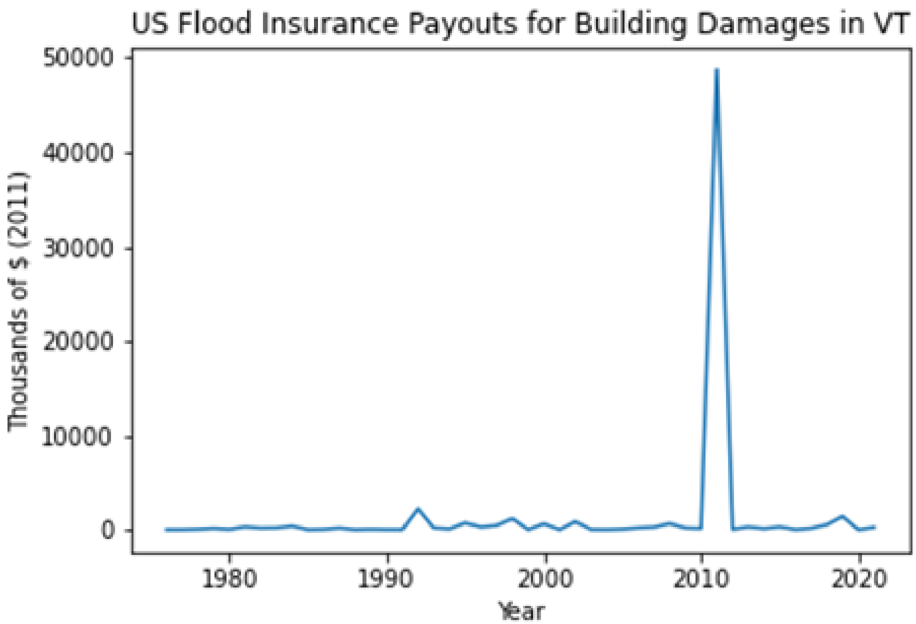
Since the devastating flooding during Tropical Storm Irene in 2011, Vermonters have been working to make our communities safer and more resilient. Climate change is expected to increase the frequency of severe storms in Vermont, making this work all the more important. Soils and vegetation high up in watersheds can play an important role in buffering peak stream-flows during storm events; protecting people, homes and infrastructure in the valleys below. Flood-control services provided by coastal wetlands, riparian wetlands and upland forests are well-studied, but very little research has been done on the impact of agricultural soil health on flood risk.

Valuing Flood Risk:

To value reductions in flood risk from soil health practices and indicators, we must ask several questions. First, what is the total, annual value of Vermont's flood risk? Second, what proportion of this risk can be attributed to agriculture? Third, how much of a difference does reducing runoff by a given amount reduce that risk?

Rare, extreme flooding events account for the vast majority of flooding damages to buildings and property. As shown in figure (X) nearly 80% of all flood damages to buildings in VT since 1976 occurred in 2011, during Hurricane Irene. Notably, the severe flooding of 1992, the 2nd most damaging event in VT since 1976, occurred in the late spring due to rapid snowmelt and ice-dams forming in rivers. This is a mode of flooding that soil-health interventions likely have little impact on.

From this, we see that our analysis should focus on "Irene-Type Flooding Events," smaller runoff-generating events appear to play only a small role in Vermont's flood risk.



Hurricane Irene resulted in an estimated $733 million in total damages[1], $860 million in 2020 dollars. We account for non-financial losses from flooding (loss of life, disruption of work and school, etc) by rounding this number up to $1 billion. Vermont sustained one other storm of this scale in the last 100 years, in 1927. To account for increased climate instability, and the potential for more frequent and severe storms, we estimate a return time of once every 25 years for an Irene-scale storm, and account for all other flood risks by lowering this to 20. Combining these numbers yields $50 million per year in annualized flood risks/damages in the state of Vermont.

What is Agriculture's Contribution to Flood Risk?

Based on the National Land-Cover Dataset, of Vermont land is in agriculture. This land is overwhelming located in places with lower value for flood run-off mitigation, because they

[1] This number is frequently cited, but I cannot find an original citation for it. The Irene Recovery Report (Rose & Ash, 2013) estimates $850 million in total assistance paid out.

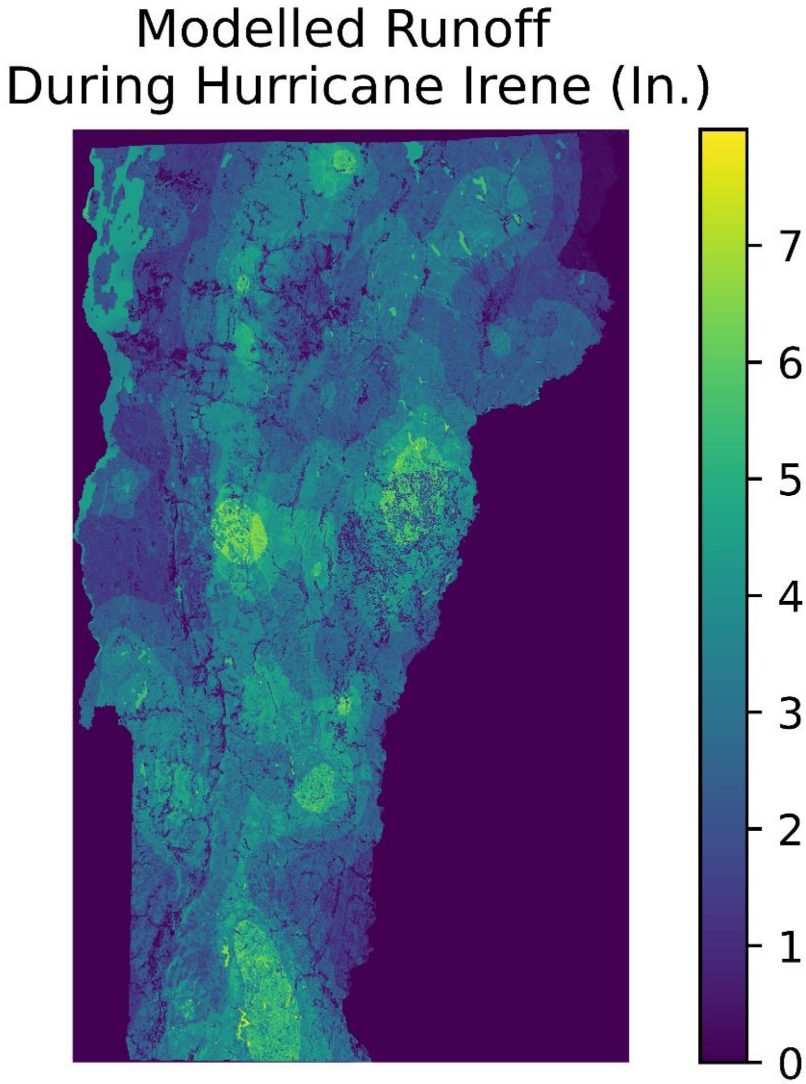
have lower elevation and lower slope. This lower-elevation land has lower flood mitigation value due to:

1- Lower rainfall at lower elevations.

2- Fewer people and structures downstream. A large proportion of farmland is very close to Lake Champlain or the Connecticut River. Figure (*) shows that the highest concentration of farmland is in areas that flow directly into Lake Champlain, and within each sub-watershed, the largest concentration of agricultural land tends to be below heavily populated areas.

3- Gentler slopes below mean little ability for run-off to gain erosive power or quickly inundate downstream areas.

An estimate using the Curve Number method yields about 10% of total run-off from agricultural lands during Hurricane Irene figure {x}. Table {y} shows the proportion of modelled total runoff from agricultural land and the proportion of agricultural land upstream for the 20 Vermont communities which received the largest disbursements of federal aid after Hurricane Irene. The low share of runoff from agriculture is mostly due to low levels of agricultural landcover upstream from


Modelled Runoff
During Hurricane Irene (In.)
0
1
2
3
4
5
6
7

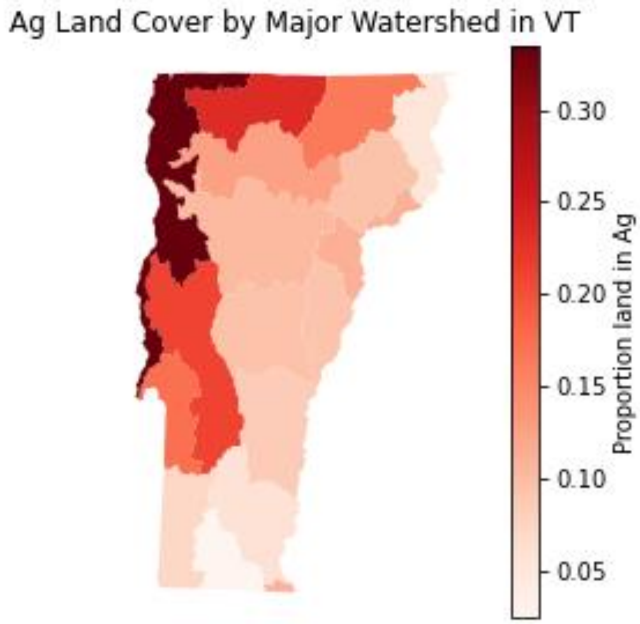
Town	% Ag Runoff	% Land in Ag
Stockbridge	1.90	2.72
Bethel	4.59	5.70
Jamaica	2.57	3.12
Woodstock	5.08	6.35
Rochester	2.00	2.84
Waterbury	7.54	9.05
Cavendish	4.77	4.77
Hartford	7.38	8.86
Bridgewater	1.74	2.24
Wilmington	3.85	4.40
Northfield	5.96	6.86
Brattleboro	5.90	7.42
Wardsboro	1.71	2.34
Ludlow	3.47	3.64
Newfane	2.38	3.18
Moretown	5.31	6.81
Grafton	1.85	2.96
Pittsfield	0.78	1.73
Chester	4.97	6.25
Halifax	7.78	8.25

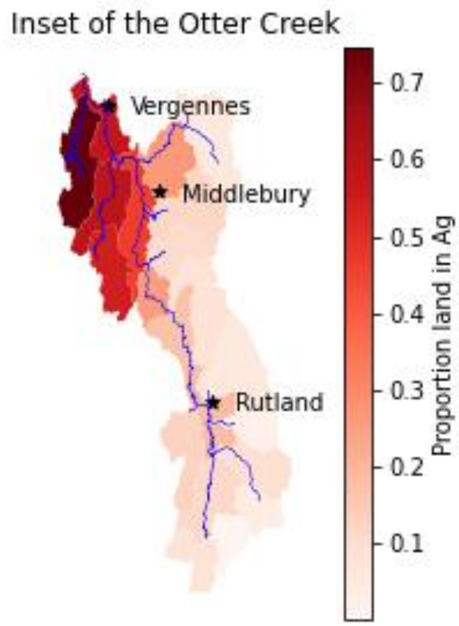
Table: Percent of Modelled Irene Runoff From Agriculture and Percent of Agricultural Landcover Upstream for the 20 VT Towns with the Largest Federal Assistance After Hurricane Irene.

Based on this sample, agriculture contributes about 6% of damage-weighted runoff in a major storm like Hurricane Irene. Assuming the flood damages increase linearly with flood runoff volumes[2], this yields $3 million dollars/year in flood risks/damages attributed to agriculture. In other words, eliminating *all* runoff from farmland would be worth approximately $3 million per year in mitigated flood damages. Total runoff from agricultural land during Hurricane Irene is estimated at 1.7 million acre-

[2] This is a dangerous assumption, but its what I have.

inches, yielding an average payment rate of $1.75/acre/year for reducing expected runoff in a major storm by 1 inch.


Ag Land Cover by Major Watershed in VT
0.30
0.25
0.20
0.15
0.10
0.05
Proportion land in Ag


Inset of the Otter Creek
Vergennes
Middlebury
Rutland
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Proportion land in Ag

Methods:

For reductions in runoff from practice changes, we use the Curve Number Method to estimate runoff volume. For very large storm events, this method is known to under-estimate runoff volumes, and thus may exaggerate impacts of practices.

For reductions in runoff from soil health, we estimate reductions using two methods, and then present the average value. First, we simply estimate the increase in excess available water-holding capacity until saturation for the soil. We estimate this value using several pedo-transfer functions and assume that the soil's plant-available water capacity is about 60% utilized at the beginning of the storm. Second, we use similar pedo-transfer functions to parameterize soils for the Green-Ampt Equation, and then simulate an 8-hour, 4-inch storm.

Results:

Current evidence supports only moderate impacts on major-storm runoff from changes in soil health or changes in soil-health practices. The below tables summarize simulation results for a major storm, with 4-inches of rainfall in 6 hours, approximating the average rainfall volume on agricultural land during hurricane Irene. With the exception of conversion of row crops to Hay, impacts are generally between 1/6 inch and ½ inch. Payments are unlikely to reach levels relevant to farmers, at least on average.

For thehigh soil-health scenario, runoff reductions range from ¼ to ½ an inch, and are estimated as about 2x as large using the simple water-deficit method as compared to process-based simulations.

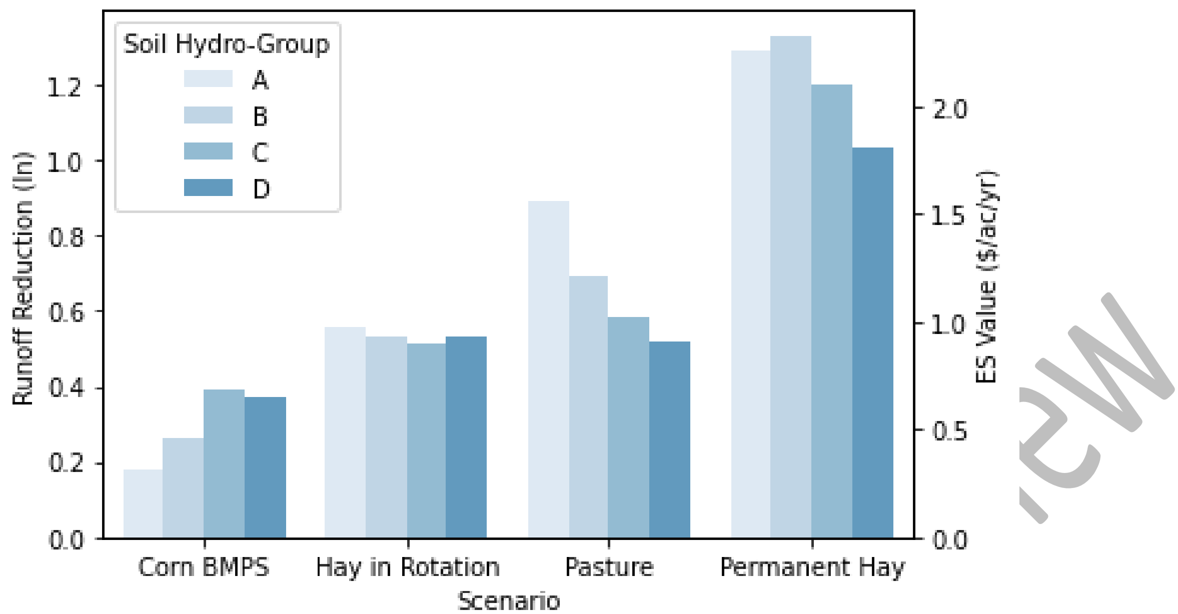


Figure (): Runoff Reductions (4-inch storm) and hypothetical Average Payments for Flood-Control Services for Changes in Soil Health by Practice (Reference Case: Row Crops, Conventional Tillage)

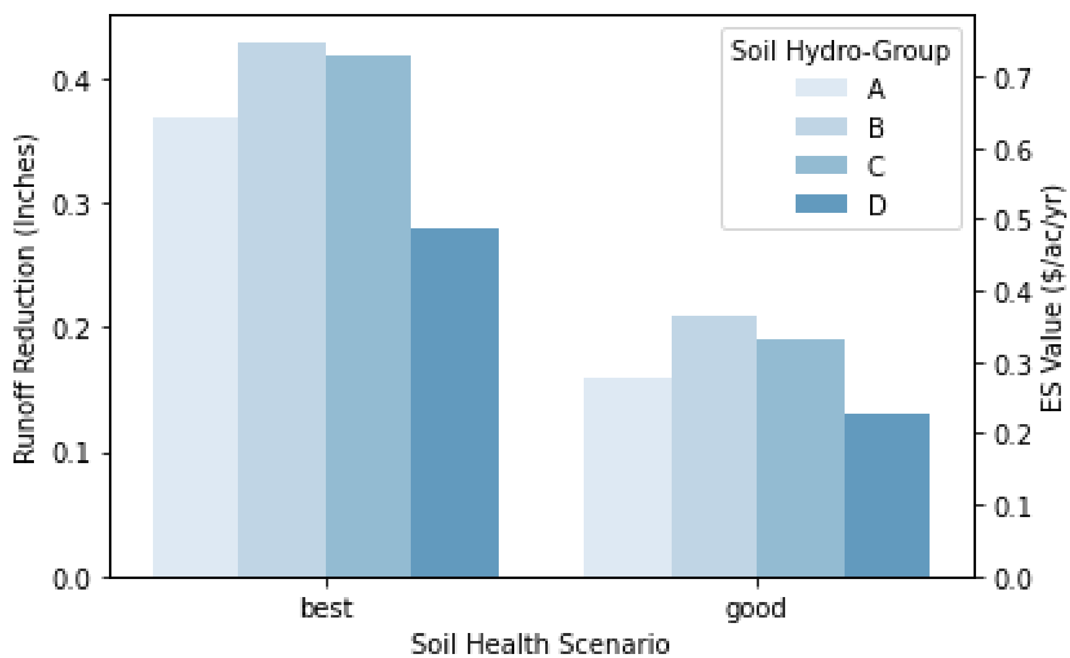


Figure (): Runoff Reductions (4-inch storm) from Moderate and Large Improvements in Soil Health.

Variation in Service provisioning and Value:

There is very little variation between soils in their capacity to improve stormflow-retention service provision, but large spatial variation in the value of stormflow mitigation. As noted before, a large proportion of Vermont farmland is at very low elevations, and many of the most at-risk communities are relatively high up in the watershed. To examine variability of potential flood-control services, we use the method described by Watson et al. (2019) to quantify spatial variability in the “demand” for flood-control services.

Our results show that most farm fields contribute very little to flood-control services, simply because they have few flood-prone structures downstream of them. On the other hand, a few farm fields in the “right” locations can contribute to protecting many at risk structures. If payments were apportioned based on flood risk, these fields could be eligible for substantial payments for their reduction in potential runoff during large storms.

ES Rate (per acre-inch)	% of Fields in Category
< $0.25	48.8%
< $0.50	23.4%
$1 - $2	10.6
$2 - $5	9.4
$5 - $10	4.3
>$10	3.0

Hypothetical Distribution of Payment Rates for Reducing Runoff in a 4-inch rain-event by 1 inch.

Climate Mitigation:

Healthy soils can mitigate climate change by storing carbon that would otherwise be in the atmosphere. Additionally, soil health and soil health practices can influence the production of methane and nitrous oxide from soils.

Non-CO2 greenhouse gases:

While we have not completed more detailed simulations, in general, increased SOM results in moderate reductions in CH_4 emissions, while decreases in bulk density can moderately reduce emissions of N_2O. In temperate cropping systems, N_2O emissions are often quite substantial, especially with substantial N inputs from fertilizer, legumes or livestock manure. Methane emissions from soils, however, are relatively small, highly variable, and even sometimes negative. In general, impacts of management on soil methane emissions are small. We discuss the general magnitude of N_2O emissions in more detail in the section on nitrogen losses.

Carbon Storage:

Globally, soils hold an enormous amount of carbon; roughly 4 times as much carbon as is currently in the atmosphere. Increasing the carbon content of soils may be an efficient way to mitigate climate change. Voluntary and regulatory markets for carbon storage provide make carbon storage in farmland by far the most commonly marketed ecosystem service from agriculture. Various schemes have enrolled millions of acres worldwide, paying farmers to capture and sequester carbon. Because soil carbon is directly measured as a soil-health indicator, there are fewer elements of uncertainty in the relationship between the soil health metrics and the ecosystem services of interest.

Valuing Carbon Storage:

There are two general approaches to valuing carbon sequestration. First, we may multiply the carbon sequestered by the Social Cost of Carbon, as calculated by the EPA, other government agencies or academic researchers. The EPA's social cost of carbon for the year 2021 is \$51/ton of CO_2. This would be equivalent to \$186/ton of soil organic matter. Alternately, we may compare them to the prices paid by voluntary or compliance-based offsets markets or other corporate programs. The Boston-based Carbon-Offset start-up Indigo Ag currently guarantees prices in range of \$10-\$15/ton of CO_2, while the company Nori allows farmers to sell offsets for \$15/ton. These prices convert to \$53 for each ton of organic carbon added to farm fields.

A major area of concern for carbon sequestration payments is permanence. If a company pays for a carbon offset, or a government pays to reduce damages from carbon, that payment assumes that this carbon is permanently removed from the atmosphere, or at least removed for many decades. If this soil carbon is instead released back into the atmosphere, only a small proportion of these damages would be averted from the short-term storage of carbon, and the value of the carbon storage is greatly reduced.

Most carbon-offset programs deal with this difficulty by enforcing contracts on farmers, obligating them to continue their climate-friendly farming practices. This option seems unlikely for a state-run PES program. Some offset-generating carbon sequestration programs assume that not all carbon will be permanently stored and may reduce payments accordingly. This approach could be taken by a soil PES program. Another approach would be to subtract the value of carbon losses from payments to the farmer generated by other ecosystem services. For purposes of this document, we use a 50% withholding rate, such that farmers are only paid for 50% of the carbon they sequester in the fields.

Carbon storage values can be annualized using the "social cost of radiative forcing" as described by Rautiainen and Lintunen (2017). From their estimates, the social benefit of withholding 1 metric ton of CO_2 from the atmosphere for 1 year is $0.45. Adjusting this value down to account for lower prices for offsets, we calculate an ecosystem service valuation of $1.09/Ton of Soil Organic Carbon for each year stored.

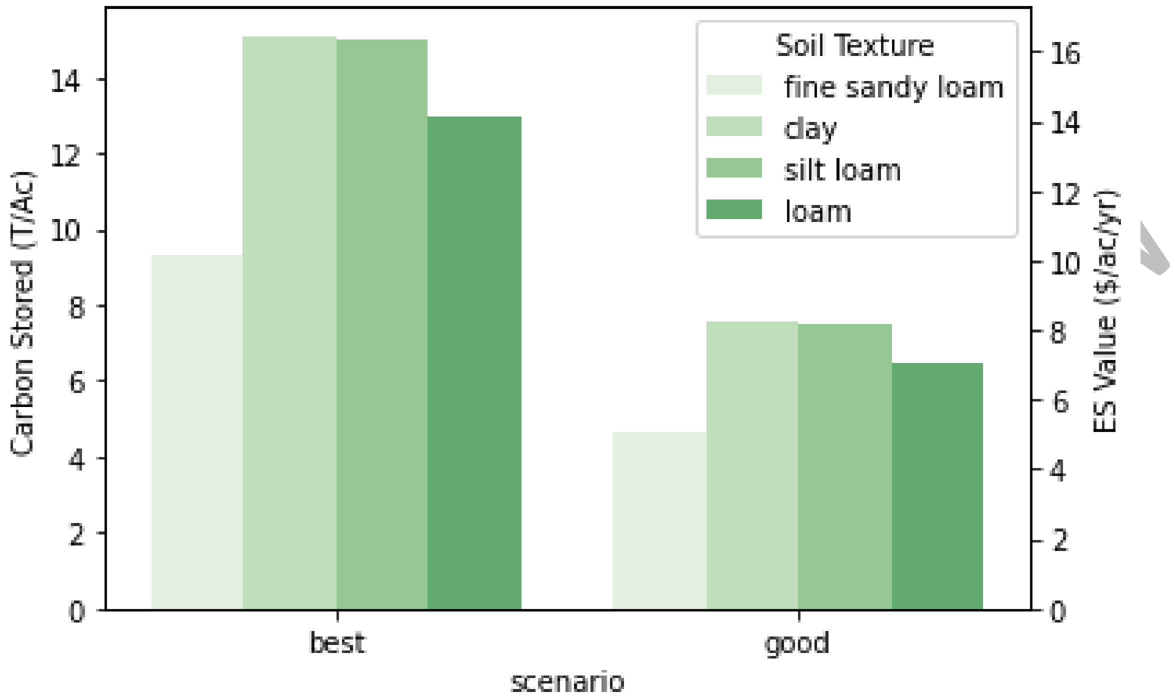
Methods:

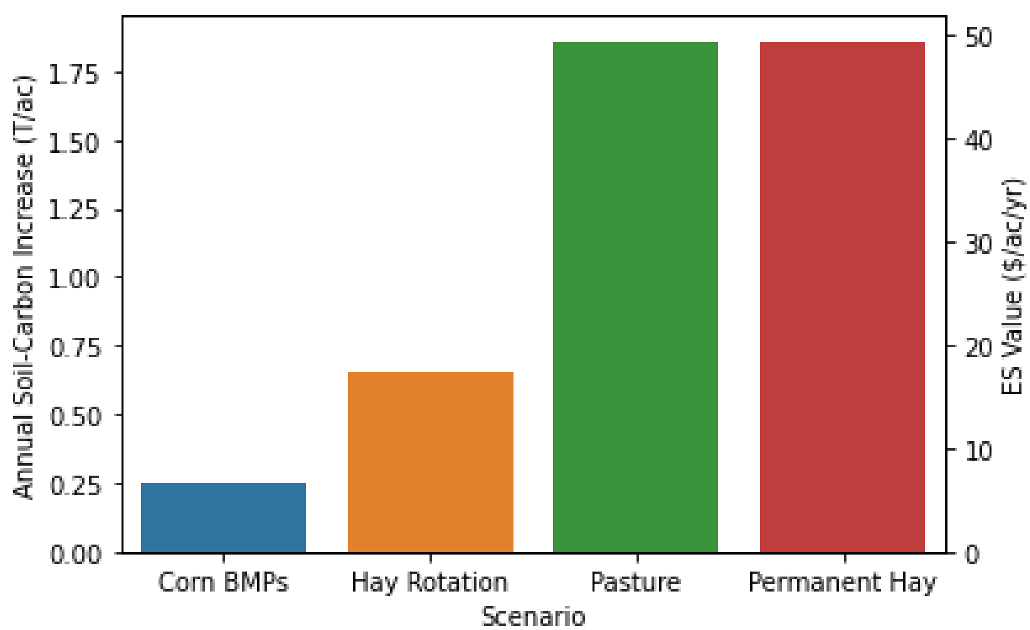
For Carbon Storage based on practices, we use estimates from the research literature compiled during task 2. For Carbon Storage based on soil health indicators, we simply use the additional carbon in the simulated soil layers.

Results:

Table {} estimates annualized increases in soil organic carbon, per acre, per year, for the soil health practices scenarios. These results are grouped by soil texture group

Table{} shows the estimated total soil carbon storage increase for the soil-health indicator scenarios. Because the soil-health indicator scenarios include carbon as a state variable, we cannot use them to estimate annual rates.





***Note that the Corn to Corn-Hay Rotation Numbers demonstrate the lack of durability in Soil Carbon increases: 5 years in Hay increases Soil Organic Matter**

dramatically, but almost half of that increase disappears when the field is rotated back into Corn for 5 years.

Variation of Service Provision and Values:

Because climate change is a global problem, the value of carbon storage is the same no matter where it is stored. For the quantity of carbon stored, farm fields with finer textures, such as clays, have more carbon storage capacity than coarse-texture soils such as sandy loams.

Measuring Carbon Storage:

Despite the one-to-one linkage between Soil Organic Matter as a soil health indicator, and carbon storage as in ecosystem service, there are important complications in measuring soil carbon storage. These relate to the depth of measurement, and its relationship to soil bulk density. Soil organic carbon is usually measured to a reference depth, often 30 cm. If management of a soil results in substantial soil compaction, then more soil material ends up within 30 cm of the surface, increasing measured soil carbon storage, without increasing actual carbon storage. Lee et al (2009) discuss these complications, and recommend that changes in bulk density not be used to assess changes in carbon storage.

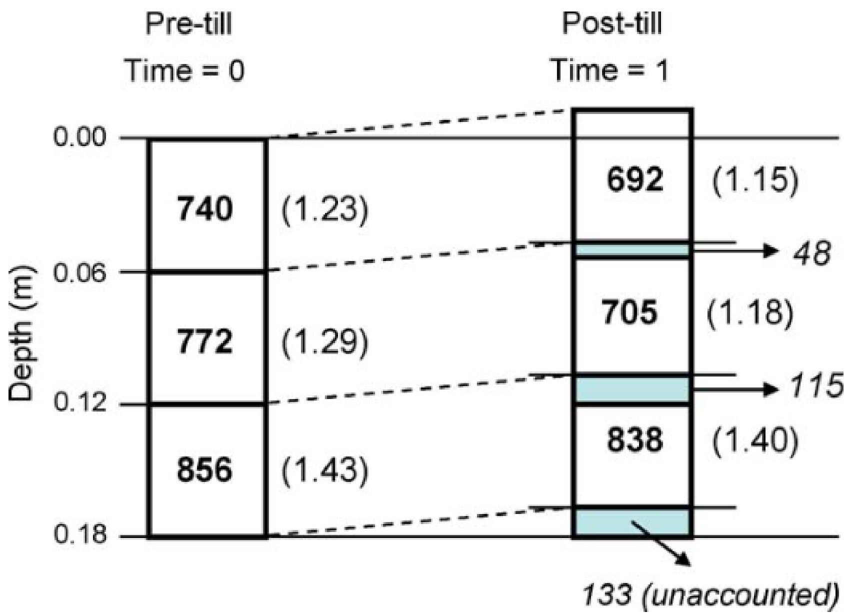


Figure (X): Tillage decreases bulk density, expanding the volume that the soil layer takes up. Because of this expansion, some carbon is now below the depth of measurement. Figure from Lee et al (2009).

Erosion:

While soil erosion is often thought of a direct threat to agricultural sustainability and productivity[3], it is also associated with many off-site environmental harms. One of the largest of these harms is the contribution of nutrients in eroded soil to eutrophication, which is covered in the Phosphorus and Nitrogen sections of this report. These costs include stream and reservoir sedimentation, which can reduce recreational value, harm wildlife, increase flood risks and reduce the working life of dams. These costs include stream and reservoir sedimentation, which can reduce recreational value, harm wildlife, increase flood risks and reduce the working life of dams.

Valuing Impacts of Soil Erosion:

For soil-erosion impacts, we use a simple “value-transfer” method. Pimentel and colleagues (1995) estimated the total non-eutrophication external costs from water-

[3] For on-farm values of erosion control, we can consider the cost of replacing organic matter lost in eroded soil. There are roughly 400 lbs of organic matter in a cubic yard of compost. If the eroded topsoil contains about 4% organic matter, then replacing organic matter requires roughly 1 ton of compost for each 5 tons of topsoil lost.

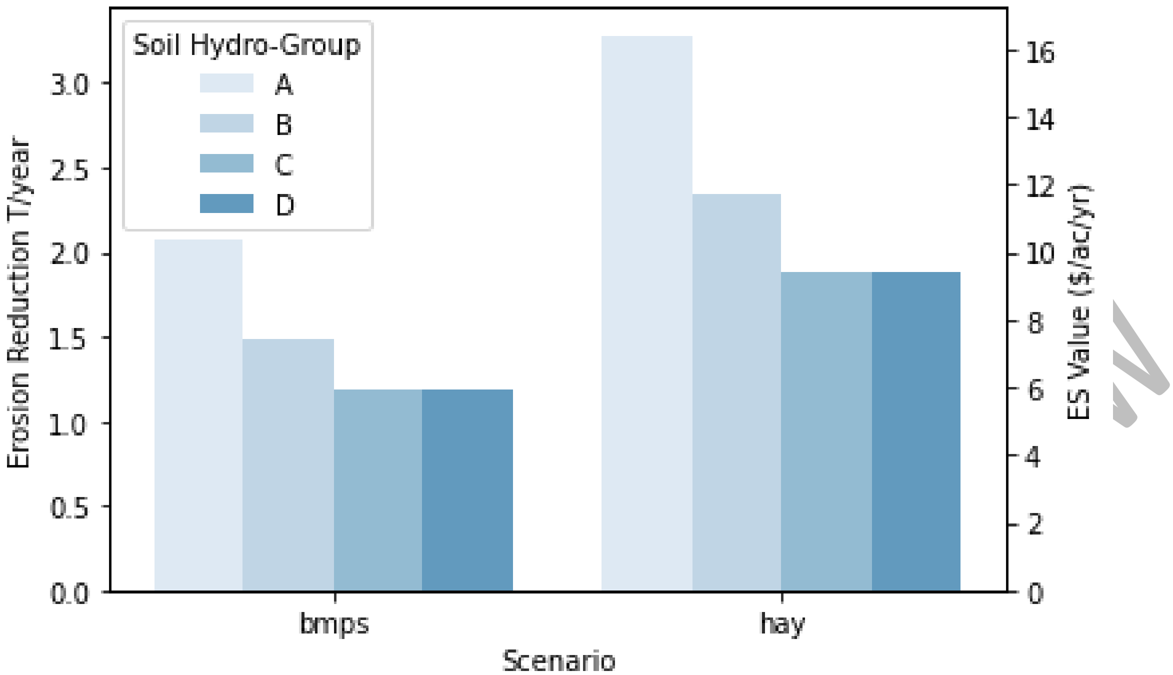
driven soil erosion for the US, and these average to \$3.50/ton. Adjusting for inflation yields \$6/ton in 2020 USD. These harms and their costs are very sensitive to waterways that the sediments eventually flow into. As such, the numbers below are merely illustrative, but they do show that erosion mitigation may constitute a substantial proportion of the public benefits of soil-health practices.

Methods for Estimating Impacts of Soil Health and Soil-Health Scenarios on Erosion:

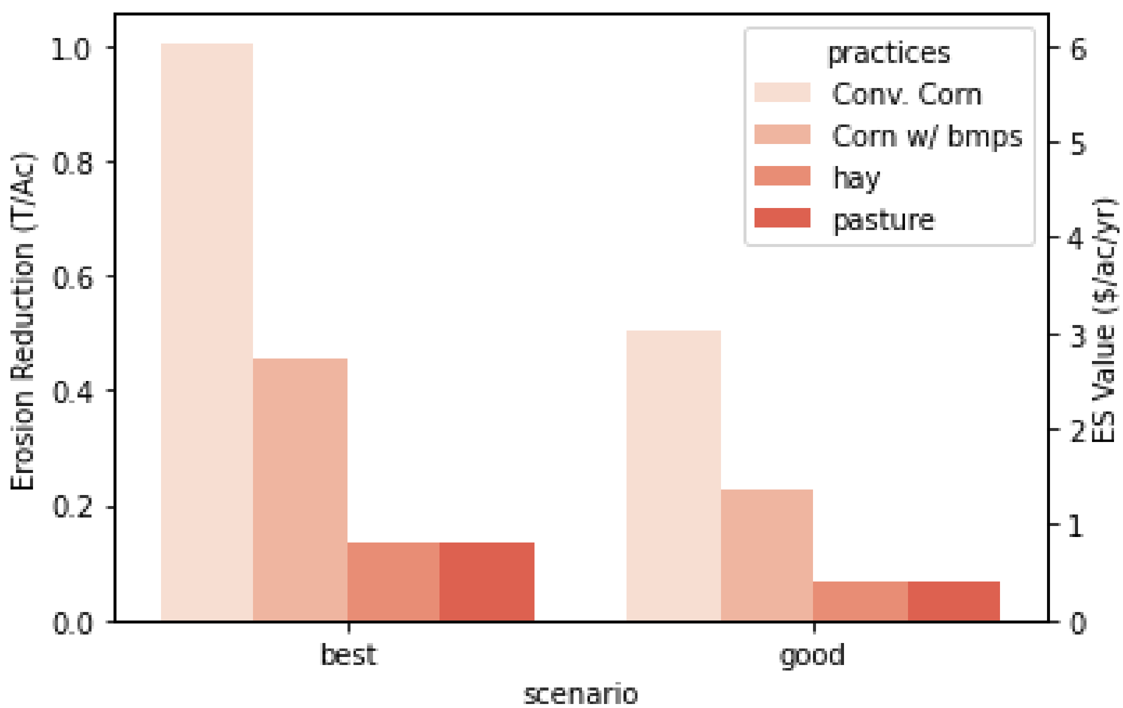
The Universal Soil Loss Equation (USLE) is a family of simple models used to estimate soil erosion losses from farm fields. One of the parameters of USLE relates directly to soil properties, the soil erodibility or “K” factor. Wischmeir and colleagues (1986) developed an equation linking soil texture, organic matter and saturated hydraulic conductivity to the K factor. We use this equation to estimate the impacts of soil health changes on soil erosion, using a family of reference scenarios for the other parameters. Likewise, for soil-health practices, we alter the “C” or crop-cover factor of USLE to develop estimates of changes in erosion losses with practice changes.

Results:

Figure {} summarizes the reduction in soil erosion from changing practices from the reference case of conventional corn. The “hay” scenario covers all perennial forages, including rotational hay, permanent hay and permanent pasture.



Soil Hydro-Group
A
B
C
D
Erosion Reduction T/year
ES Value ($/ac/yr)
bmps
hay
Scenario
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0
2
4
6
8
10
12
14
16



practices
Conv. Corn
Corn w/ bmps
hay
pasture
Erosion Reduction (T/Ac)
ES Value ($/ac/yr)
best
good
scenario
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2
3
4
5
6

Sources of Variation:

The value of erosion reduction services from healthy soil is higher on fields with higher on fields with steeper slopes, and higher on fields growing annual crops than those with perennial vegetation. We expect the same magnitude of soil-health improvements to have the same percentage impact on soil erosion, making the economic value much larger on fields that have high potential for erosion losses. The spatial variability in the value of damages done by a ton of eroded sediment is likely significant, but not explored in this study.

Phosphorus Losses:

Phosphorus enrichment is the largest source of freshwater eutrophication globally, and agriculture is the largest contributor. This is also true in Vermont for both the Lake Champlain and Lake Memphramagog watersheds. In Lake Champlain, numerous algae blooms have degraded water quality, causing major economic, quality-of-life and health impacts on the people living near the lake. Healthy soils and some soil-health related practices may be helpful for retaining Phosphorus on farm fields and keeping it out of freshwater bodies.

Caveats:

Soil health metrics, and soil health practices can be effectively linked to expected reductions in erosion and runoff, nutrient losses through these pathways are proportional to these quantities, holding all else equal. Greater water infiltration may, however, increase nutrient losses downward through the soil profile, which may be especially harmful in soils with pattern tile drainage, or other direct connections to waterways via subsurface flow.

These results should be interpreted with caution. The estimates for *soil-health practices* are directly drawn from the Vermont P-Index, and therefore reflect the feedback that farmers are already getting about how to reduce their contributions to P loading.

However, this information may be useful for thinking about how a soil-health program might be integrated with the VT Pay-for-Phosphorus program and other initiatives to reduce P losses into the environment.

Valuing P Reductions:

Estimating the marginal harms from an additional lb. of Phosphorus emitted into Lake Champlain is beyond our capabilities for this short report. Instead, we use estimated costs of required WWTF upgrades, and calculate their marginal cost of P reduction. This approach assumes that the state of VT will make large investments in mitigating P loss, and that the state is ambivalent to where those reductions come from. We estimate the abatement curves for Phosphorus from WWTFs using data from the Lake Champlain TMDL and the Vermont DEC. Two abatement curves are used: one which uses the current wastewater load (in millions of gallons / day), and the other that uses the permitted load. By taking the average of these two curves at the 85th percentile, we calculate an abatement cost of $100/ton (Figure). The TMDL and other P-reduction plans focus on agriculture for the largest reductions in part because these are believed to be more cost-effective, so $100/ton places an upper-bound on payments. Given that approximately 75% of Vermont’s agricultural land is in the Lake Champlain or Lake Memphramagog watersheds, the average value of P reduction is $75/lb.

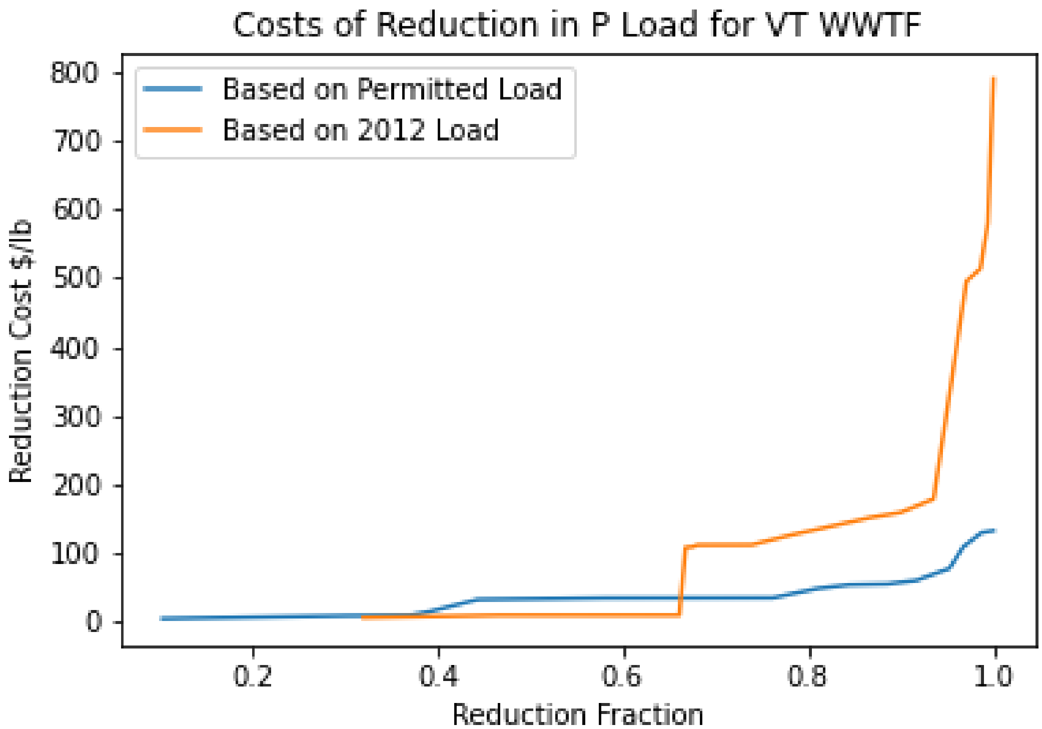


Figure {}: Abatement Curves Estimated for Reducing Phosphorus Loads from Wastewater Treatment Plants in Vermont

Methods for Estimating Reductions:

To estimate reductions in P losses, we use the VT P Index, a spreadsheet-based model used by farmers for nutrient management planning. The VT P Index includes most soil-health practices that we are interested in, and we were able to incorporate changes in soil health indicators in two ways. First, the P Index requires an erosion rate, for this we utilize the impacts on erosion losses developed previously. Second, we simulate the impacts on runoff across a wide variety of storms using the same methods as described in the section on flooding, to estimate how soil health reduces growing-season runoff, and therefore P losses in that runoff.

Results:

Figure {} shows the estimated reductions in P losses for practice changes, relative to conventional corn. Reductions for the hydro-group D are likely misleading, as these soils are not usually cultivated for row-crops without pattern tile drainage.

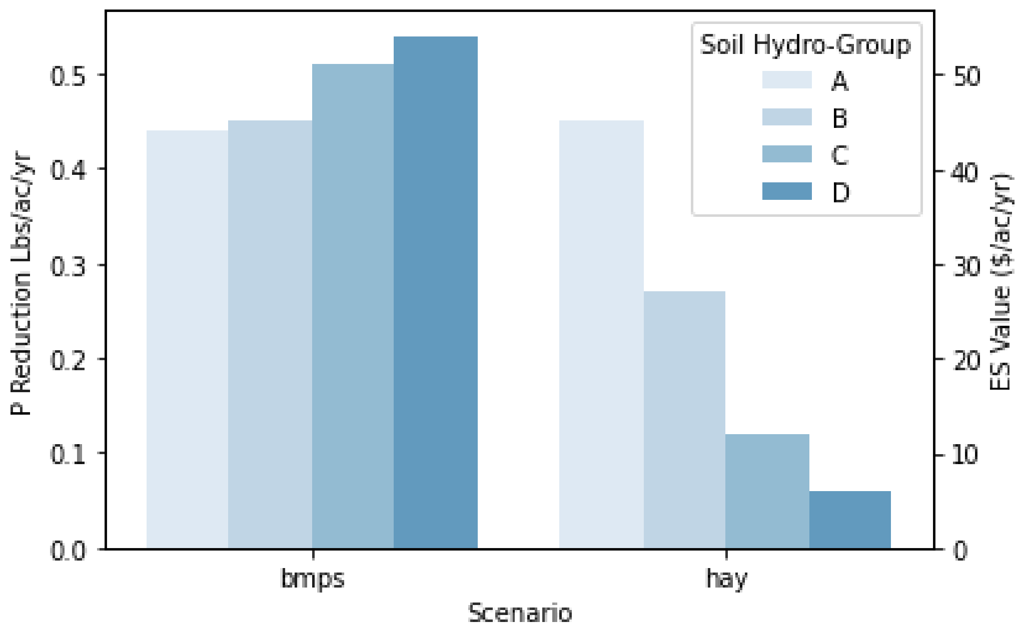
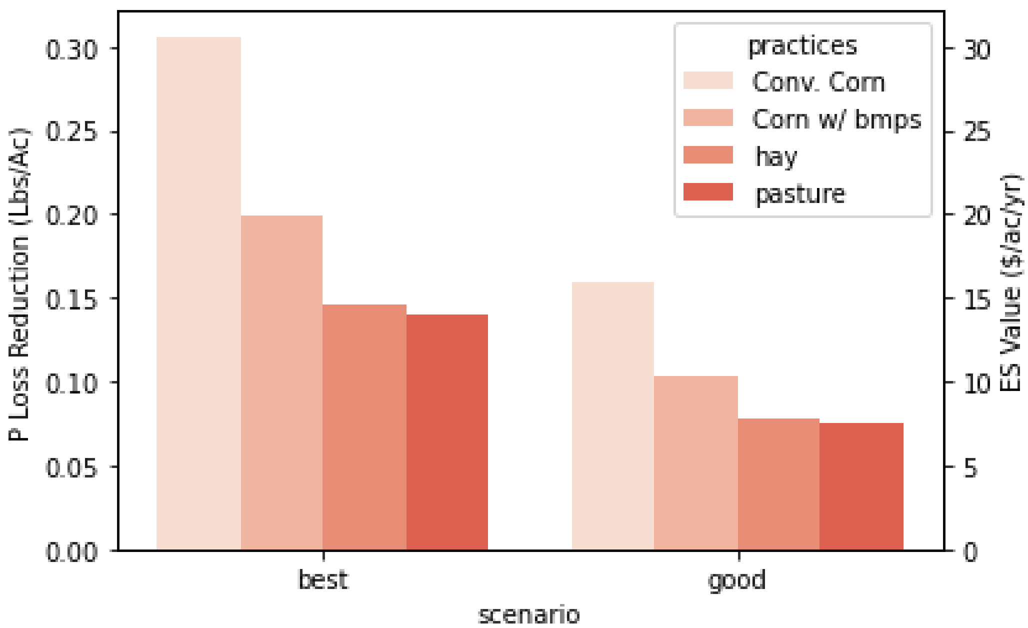


Figure {} shows our results for the soil improvement scenarios.



Sources of Variation in Service Value:

Improved soil health can reduce erosion and can reduce runoff, which are two important pathways for Phosphorus losses from farm fields. All else equal, we should expect reductions erosion and runoff to be proportional to P losses from erosion and runoff. As noted above, these reductions in P loss may be largely or fully offset by increased subsoil losses of P, on fields with substantial connections to waterways via subsurface drainage. Similar to erosion-control, the quantity of P-retention services provided by healthy soils is proportional to the field's potential to lose Phosphorus. Healthy soils provide a greater benefit in P reduction on fields growing annual crops, on steeper slopes, closer to waterways. Therefore, a large increase in soil health has a smaller value if other P-conserving practices are already implemented.

Beyond this analysis, most important soil-health indicator for P loss is **soil test phosphorus**. High soil-test phosphorus levels make it extremely difficult to keep P losses from farm fields to acceptable levels.

The largest source of variation in the value of P retention services is location in a sub-watershed. P retention is much more valuable in the basins of Lakes Champlain and Memphramagog than it is in watersheds connected to the Connecticut and Hudson Rivers. It may be even more valuable in specific sub-watersheds flowing into highly impaired lakes and ponds.

Nitrogen:

There are several types of N losses from agriculture which harm ecosystems and human health through a variety of pathways. Gaseous losses, including ammonia, nitric oxides and nitrogen dioxide contribute to acidification of water and soil, and can damage air quality both directly and through their impacts on particulate formation. Water-borne losses of nitrate, including leaching and runoff, can damage drinking water resources and contribute to eutrophication of marine ecosystems. Nitrogen lost from the soil can also change form after leaving the soil - nitrate in runoff will eventually be denitrified and turn into N2O, NO or NO2, while some gaseous emissions will be deposited in soils that they may subsequently leach from.

Valuing N Losses:

The spatial complexity of N emissions and their harms calls for a full study of its own, but the table below summarizes best-estimates of the average economic harms done by different pathways of reactive nitrogen emissions in the United States. Note that some of these, such as respiratory disease, may have much smaller impacts in VT, which has low population density and few population centers downwind.

N Loss Pathway	Damage Valuation per Lb of N	Largest component	Note
NOx	$15.88	Respiratory Disease (79%)	Climate is (-)
NH3	$6.07	Ecosystem Change (69%)	Climate number is (-)
N2O	$11.11	Climate Change (87%)	Climate number from (Marten & Newbold, 2012)
Surface freshwater	$10.33	Eutrophication (85%)	
Groundwater	$1.33	Colon Cancer (72%)	
Costal Water	$12.12	Fisheries (71%)	

Table {}: Average US Values for Damage costs from Different types of Nitrogen Emissions, based on Sobota et al (2015).

Impacts of Soil Health on N Losses:

In general, improving soil organic matter increases N mineralization, which may somewhat increase soil N losses. This impact may be reduced if farmers compensate by applying less N to their fields in manure and fertilizer. Decreases in bulk density can significantly decrease N2O losses and runoff losses but may substantially increase losses through leaching. Table {X} Provides example data for N losses from dairy-based cropping systems in VT, and the economic valuation of a 25% decline of N losses through each pathway. The social benefits of reducing N losses to this degree are substantial, larger than most other ecosystem service benefits.

Some soil health practices may actually increase N losses. For example, in a recent dairy cropping systems experiment, the Corn BMP scenario substantially increased gaseous N losses when compared to more standard agronomic practices. Detailed modelling on how soil-health changes may impact soil nitrogen status is technically feasible but would take more time than we had for producing this report.

	Hay		**Corn**	
	Lbs/Ac/Year	**Value 25% decrease**	**Lbs/Ac/Year**	**Value 25% decrease**
Leaching	**4**	**$1**	**6**	**$2**
Runoff	**8**	**$18**	**Negligible**	**0**
N2O	**2**	**$14**	**8**	**$19**
NH3	**6**	**$3**	**6**	**$8**
Total		**$36**		**$29**

Valuation of Soil Biodiversity:

Several options exist for valuing soil biodiversity, though none of these are feasible within the scope of this study. There are 3 general types of values contributed by soil biodiversity. First, soil biodiversity is linked to supporting ecosystem services including nutrient cycling, predation, and soil aggregation, which may enhance other ecosystem services, including crop production and the services discussed in this paper. Second, soil biodiversity may have insurance value: soil biodiversity may enhance the resilience and stability of important soil ecosystem services. Lastly, soil biodiversity may have existence value, the people in Vermont may derive economic value from knowing that their soils are biodiverse, regardless of any direct impacts on human-wellbeing.

The first two types of value are important questions, but too little research exists to conduct a meaningful valuation. For existence value, stated-preference methods, such as contingent valuation surveys could be used to understand Vermonter's willingness-to-pay to improve soil biodiversity, but these methods would likely be unreliable for something so abstract.

Conclusion: